Estuarine Sediment Budgets for Chesapeake Bay Tributaries

by Julie D. Herman

PURPOSE. This Coastal and Hydraulics Engineering Technical Note (CHETN) summarizes estuarine suspended sediment budgets developed for several estuaries of the Chesapeake Bay in Maryland and Virginia (Herman and Friedrichs 2010). These sediment budgets provide better understanding of sediment transport patterns and pathways, and will aid in improving Regional Sediment Management (RSM) practices in the US Army Engineer Districts, Baltimore and Norfolk. Sediment budgets were calculated for the Patuxent River, Maryland; York River, Virginia; and a partial budget was developed for the Potomac River, Maryland.

BACKGROUND.

Sediment Budgets. Sediment budgets account for the sources (areas of erosion) and sinks (areas of deposition) of sediment in a specified area over a specified time frame. The components of a sediment budget may vary depending on spatial and temporal scales, local variables, and available data. Sediment budgets can identify types and locations of missing data that could help direct future research needs for additional data collection. Also, sediment budgets may assist significantly in improving management decisions.

The sources and sinks in a sediment budget are calculated as sediment loads, and the loads are related in a mass balance equation. Load is mass per unit of time. This study used metric tons per year (Mt/yr), where a metric ton is 1,000 kg. Figure 1 displays the conceptual model of the sediment budget for Chesapeake Bay estuaries.

Study Areas. The York and Patuxent Rivers were chosen to represent Virginia and Maryland, respectively, because these well-studied river systems have the necessary data to calculate sediment budgets. The study revealed problems unique to datasets for each state during the first phase of the project. With data issues resolved, the Potomac River was chosen because it is the largest estuary of the Bay (the Bay is the estuary for the Susquehanna River) and the focus of many state and Federal agencies. Sediment data from the Chesapeake Bay Program (CBP) water quality monitoring stations in the tributaries were used to study sediment transport. Stations were chosen by location (Figure 2). The "original" stations were the head and mouth of the estuaries, and the "additional" stations were added for a better understanding of sediment transport within the estuaries. The water quality monitoring stations have CBP identifications, in which the prefix "LE" denotes "lower estuary" and "RET" denotes "river-estuary transition."

While the watersheds of these rivers differ greatly in relief, areal extent, soil type, land use, etc., the estuaries for all the systems are limited to the low-relief Coastal Plain. Land use ranges from predominantly forested in the York River watershed to a mix of developed, agricultural and forested in the Patuxent River and Potomac River watersheds. Water quality monitoring stations used to calculate estuarine loads were located only in the brackish part of each system. All the

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systems have a main channel that varies in depth and tends to shallow upstream, flanked by broad shoals about 2 m deep.

Sediment Budget: Mass Balance Equation

load at head of estuary + shoreline erosion + accumulation in estuary + *in situ* biogenic production + load at mouth of estuary = 0

River

Load at head of estuary

Shoreline erosion

Accumulation in the estuary

In situ biogenic production (mid-Bay tributaries)

Bay

Load at mouth of estuary

• Positive values are sources, negative values are sinks.
• If equation does not equal 0, the remainder is the error.
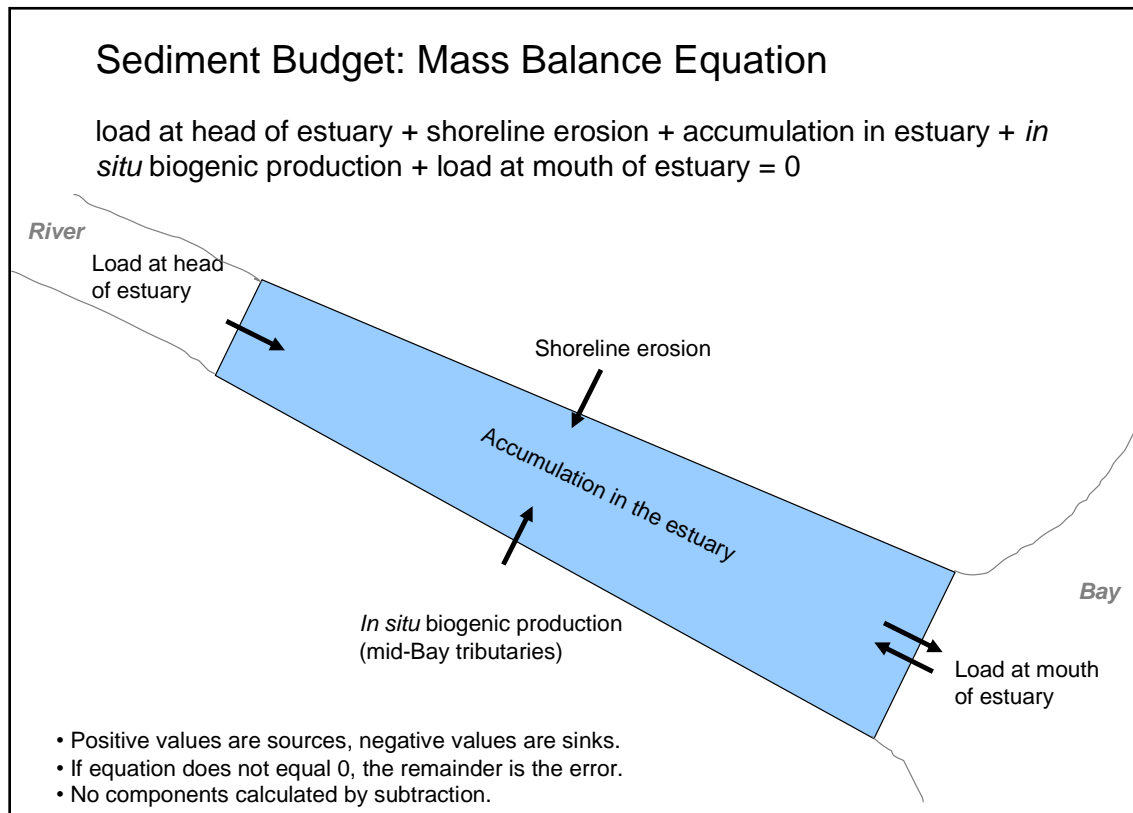• No components calculated by subtraction.

Figure 1. Conceptual sediment budget for Chesapeake Bay estuaries.

Sediment Data. In this study, suspended sediment was represented using total suspended solids (TSS), which consists of both inorganic and organic particles. The US Geological Survey (USGS) is now using suspended sediment concentrations (SSC) at Fall Line monitoring stations, but these are essentially unavailable in the estuarine portions of the Bay. Due to laboratory processing, TSS samples are skewed towards finer sediments compared to SSC. While they are not precisely comparable, and there is no easy conversion factor (Gray et al. 2000, Glysson et al. 2000), TSS are measured Bay-wide and many stations have a long period of record (tens of years). Because of data availability and for consistency, TSS were used everywhere in this study.

SEDIMENT BUDGET COMPONENTS.

Estuarine Sediment Loads. Calculating suspended sediment loads in estuaries is difficult because of the complex nature of water movement in these systems. Multiple estuarine transport processes, such as gravitational circulation, tidal pumping, and river flow all contribute a portion of the suspended sediment load. In this text (for uniformity), the processes are called gravitational transport, tidal transport, and river transport, respectively. The most commonly used sediment loads for Virginia tributaries (Schubel and Carter 1976) were based on a salt balance using a single year's data at a station in the main stem of the Bay. A new methodology using sediment data from tributary water quality monitoring stations was developed subsequently
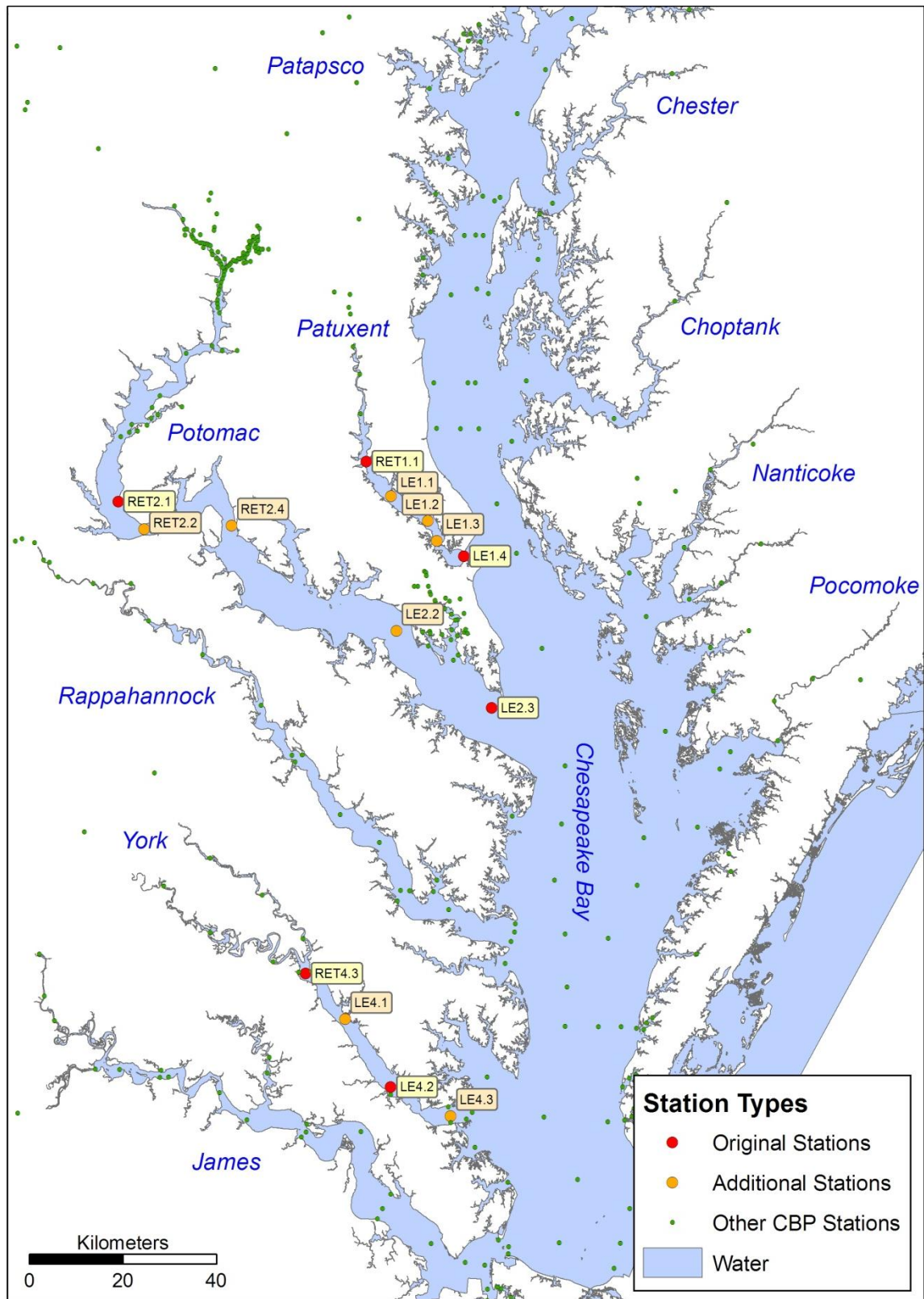
Figure 2. Estuaries and water quality monitoring stations. LE denotes lower estuary; RET denotes river-estuary transition.

(Herman 2001) and improved on here to estimate several important aspects of suspended sediments in estuaries, including the magnitudes and directions of estuarine transport processes and the calculation of suspended sediment loads (mean annual values) in the estuaries.

The basic concept is that concentration multiplied by velocity, and then integrated over the cross-sectional area, equals the sediment load.

$$Q \ = \ \int (u * c * dA) \hspace{4cm} \text{Equation (1)}$$

where Q is load, u is velocity, c is concentration, A is cross-sectional area, and dA represents the components of the total area over which the integration is summed.

For this study, it was assumed that the tributaries have a typical two-layer circulation in a partially stratified estuary (Haas 1977, Owen 1969, Lin and Kuo 2001). In a tidal system with two-layer circulation, the load for the upper and lower layers must be integrated separately before combining into a total load. It is assumed that, in each of the two layers, it is reasonable to represent the velocity and concentration via representative layer-averaged values.

$$Q_{layer} \ = \ [(u_{tidal\ transport} * c) \ + \ (u_{gravitational\ transport} * c) \ + \ (u_{river\ transport} * c)] * A_{layer} \hspace{1cm} \text{Equation (2)}$$

$$Q_{total} \ = \ Q_{upper\ layer} \ + \ Q_{lower\ layer} \hspace{4cm} \text{Equation (3)}$$

where u (m/s) was calculated from Chesapeake Bay hydrodynamic model output (1985-2005), c (mg/l, converted to g/m^3) is TSS concentrations from Virginia and Maryland water quality monitoring stations, and A (m^2) was calculated using National Oceanic and Atmospheric Administration (NOAA) bathymetric data.

The velocities attributed to tidal and gravitational transport were extracted from the hydrodynamic model output, and river discharges from USGS gauging stations were used for the river transport. For each transport process, the data from the 1985-2005 time period were plotted on a single graph versus tidal phase. Figure 3 shows sample graphs for station LE4.2 in the York River. These displays are useful for elucidating patterns in sediment transport. For example, multiplying TSS concentrations by tidal velocities yields the tidal transport graph that shows greater transport on flood tide in the lower layer of the York River at station LE4.2, off Gloucester Point.

Estuarine Sediment Accumulation. Sediment accumulation in estuaries was calculated using bathymetric data from two distinct time periods that differ for each river. For the York River, the dates were 1857 and 1945; for the Patuxent River, the dates were 1944 and 1985; and for the Potomac River, the dates were 1862 and 1955. Bathymetric data were from hydrographic surveys conducted by the NOAA National Ocean Service and are available in digital format online (National Oceanic and Atmospheric Administration 2012). Some of the older surveys are unavailable in digital format and were digitized previously by the Virginia Institute of Marine Science staff. The soundings for the older dataset were adjusted for the difference in relative sea level rise with the newer dataset. The two sets of surveys were each converted into a bathymetric surface with ArcGIS, a geographic information system, using an
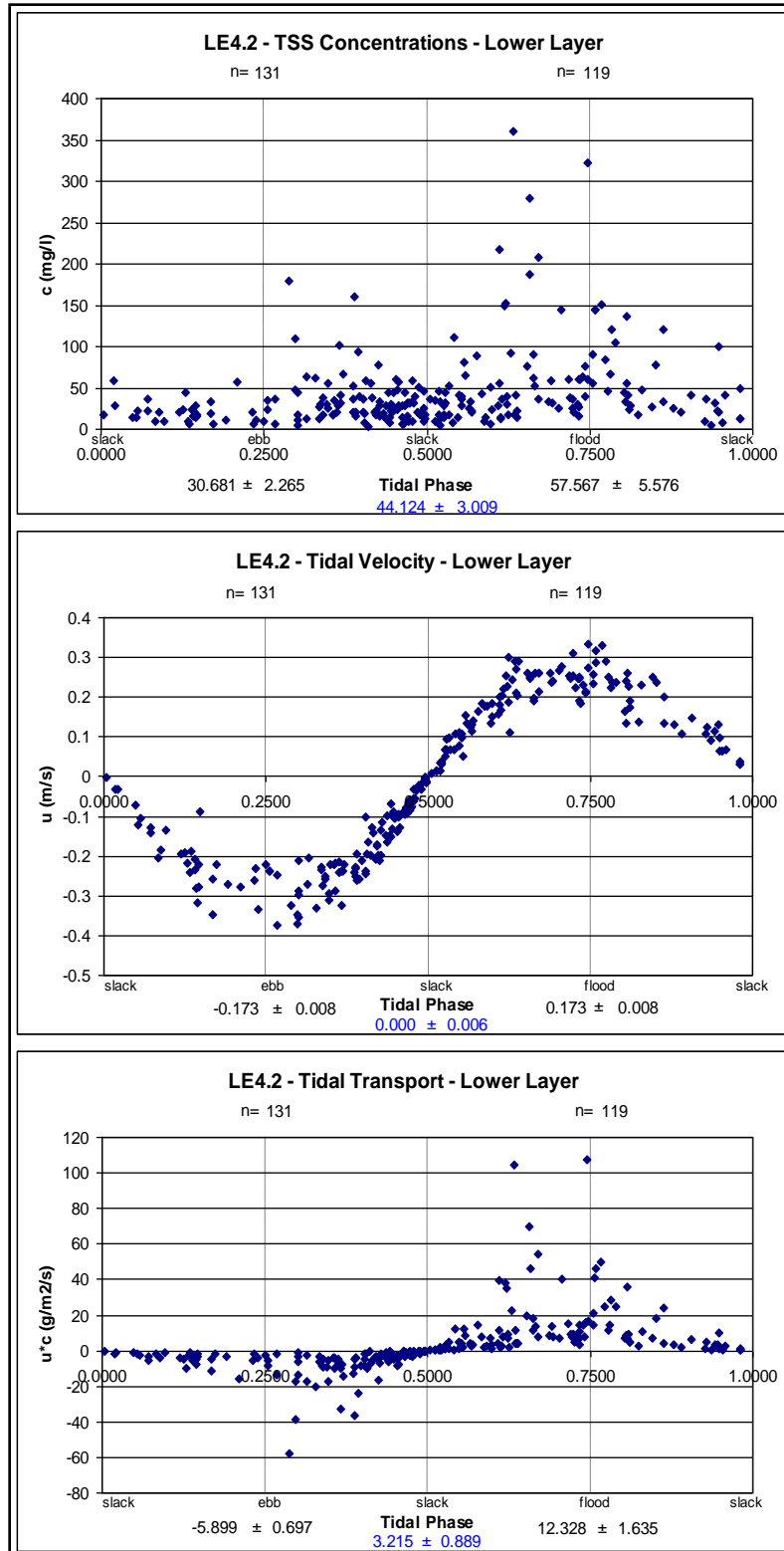
Figure 3. TSS concentrations, tidal velocities, and tidal transport for station LE4.2. Means and standard errors of ebb and flood phases are in black. Total mean and standard errors are in blue. When applying the results of this study, it is recommended that all values be rounded to two significant figures.

interpolation method that creates triangulated irregular networks (TINs). The two surfaces were then subtracted and a volume change (m^3) was calculated (Figure 4).
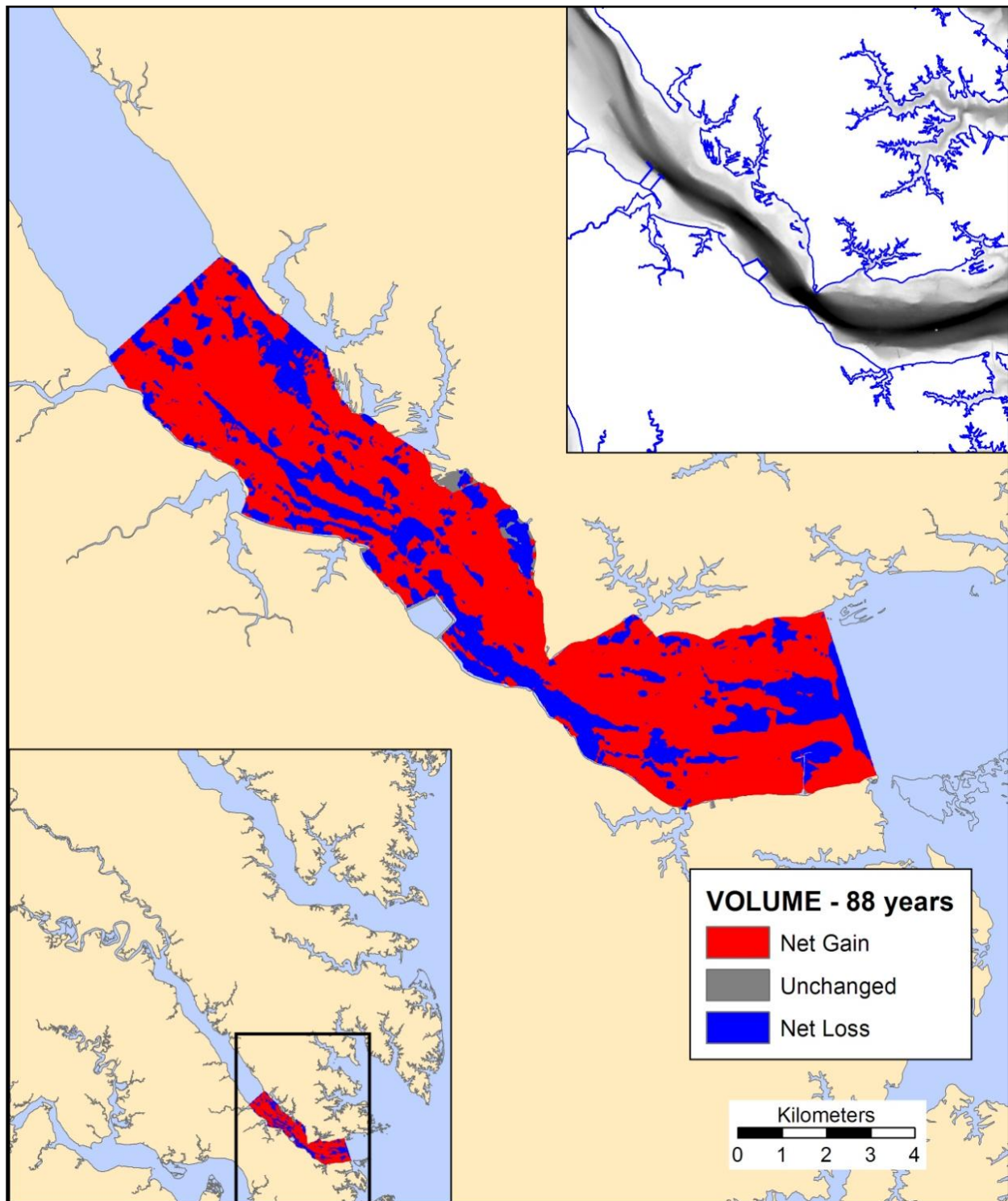

Figure 4. Estuarine sediment accumulation in the York River using TINs created with bathymetry from 1857 and 1945. Upper inset shows location of channels (dark gray) and shoals (light gray). Lower inset shows location of bathymetric change data.

Shoreline Erosion. Shoreline erosion, SE, was calculated by determining the volume of material input along each reach of undefended shoreline:

SE = [(reach length) * (average bank height) * (average erosion rate)]   Equation (4)

Data came from several sources including historical erosion rates (Maryland Geological Society 2012) and LIDAR (LIght Detection And Ranging) data from Maryland, and digital terrain models (State of Virginia 2012) and historical bank erosion studies (Hardaway et al. 1992) from Virginia.

Shoreline erosion consists of fastland (subaerial) and nearshore (subaqueous) erosion. Only fastland erosion was calculated for the budgets because nearshore erosion often is a much smaller proportion of shoreline erosion (Hardaway et al. 2009). Additionally, nearshore erosion is captured in part by the estuarine sediment accumulation term, and separating eroding sediment from resuspended sediment in the nearshore is problematic.

Biogenic Production. Currently, it is thought that biogenic production may be a substantial portion of sediment sources in mid-Bay estuaries (Cronin et al. 2003). Biogenic silica values were collected from numerous samples in the Rappahannock River (Anderson 1982). Concentrations for all stations in the estuary for all seasons were averaged to obtain a mean concentration of 0.15 mg/l. The contribution from biogenic production using this mean concentration is quite small; in the Patuxent River, it is less than 1% of the smallest source.

Another important consideration is the use of TSS data, which already incorporates most or all of the biogenic production so that a separate term in the sediment budget was deemed unnecessary. Both TSS and SSC contain inorganic sediment (e.g., sand, silt, clay), organic material from runoff (e.g., leaves, peat) and *in situ* biogenic production (e.g., diatoms, foraminifera). Fixed suspended solids (FSS) are the remains when TSS samples are heated to remove the volatile organic material. Although the volatile material is burned off, the organic tests of the microorganisms remain. Therefore, the biogenic production term in these sediment budgets was assigned a value of 0.

DISCUSSION. Sediment budgets for the York River, Patuxent River, and Potomac River (partial budget) are shown in Figures 5 through 7. To illustrate the dynamic nature of these systems, sediment budgets include intermediary loads in the estuaries as well as those at the head and mouth. The results of this study represent the most comprehensive calculations to date of sediment loads for Bay tributaries.

Although the rivers show different magnitudes and transport directions of sediment loads, averaging all the loads for each river shows a net input of sediment into each estuary, supporting the traditional thinking that tributaries are sinks of sediment from the Bay (Figure 8). Additionally, the absolute value of the total average load for each river decreases from south to north in the Bay especially when normalized by river cross-sectional area. Total average loads from the James and Rappahannock Rivers are needed to confirm or challenge this pattern. This tendency for decreasing absolute load to the north is consistent with decreasing tidal range along this portion of the Bay main-stem and, thus, decreasing magnitude of tidal resuspension.

Budgets for the York and Patuxent Rivers both show a sediment loss that is unaccounted for (i.e., to balance the budget so the error term is zero, more sediment is needed from sources, or the sinks are too large and need to be reduced). Many factors contribute to the error term in a sediment budget mass balance equation. The main causes are spatial scales, temporal scales, and missing data. All efforts were made to recognize these differences and the effects they may have on the results. One way to help reduce inconsistencies is to calculate a value for each component of the sediment budget, so that no components were determined by subtraction. This puts the errors from all the components into one term, which then can be analyzed and apportioned to possible causes.
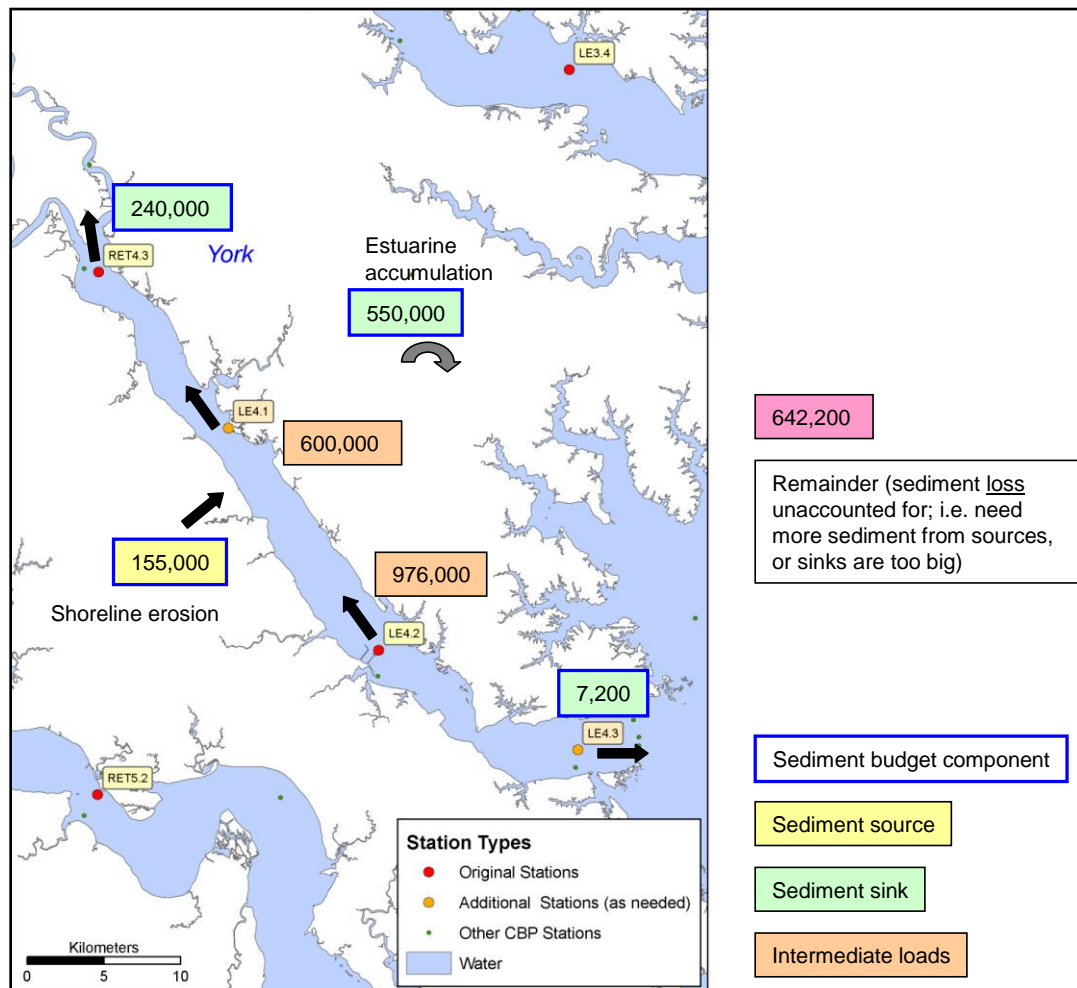

Figure 5. York River estuarine sediment loads and budget. Loads are in Mt/yr.

Long-term pre-existing datasets provide unique challenges, but also provide a different perspective from using short-term localized monitoring. Ideally, data for all budget components would be collected over the same time span, but in reality, this rarely occurs. In general, geomorphic rates for shorter time spans are higher and more variable, so the longer time spans may be more comparable. Despite these issues, the results in this study are based on the best available data. As new data are collected, future iterations of the budgets will improve.
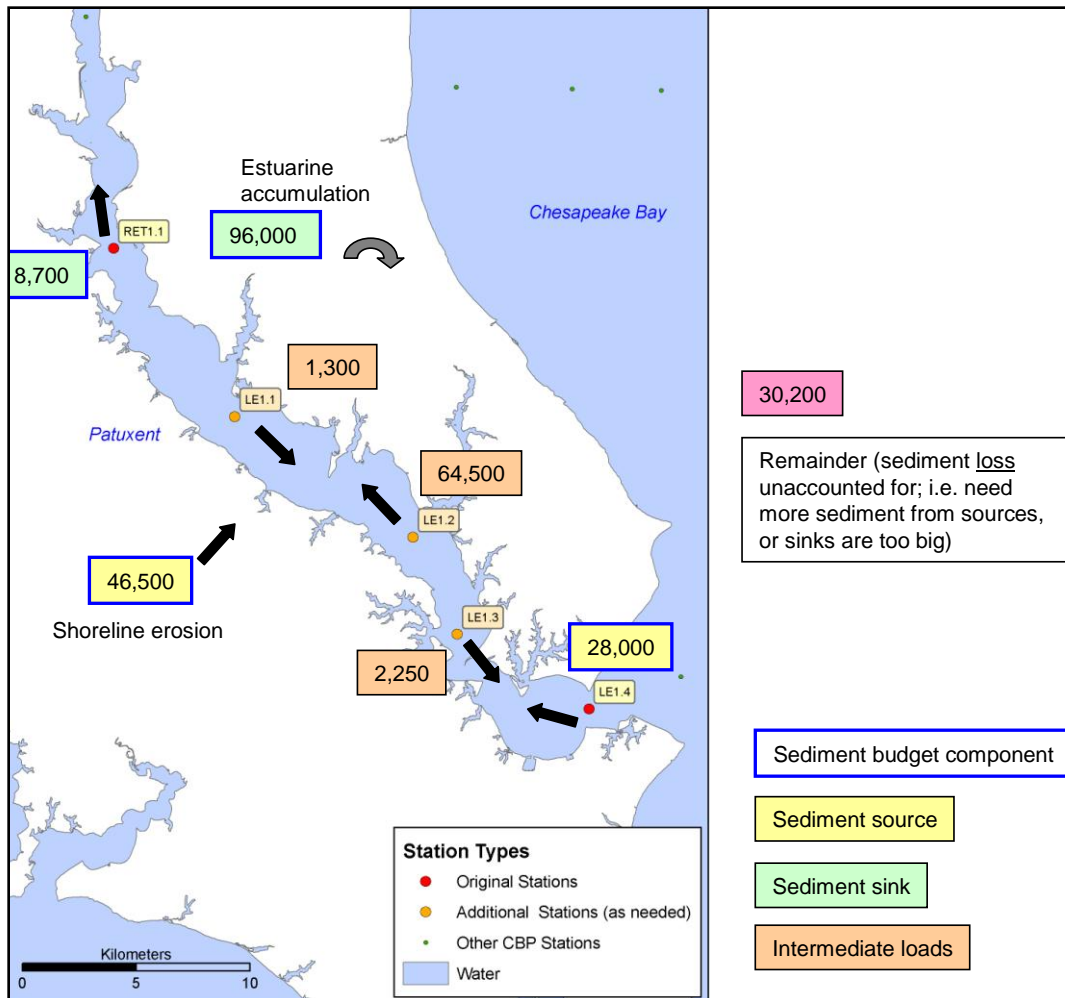
Figure 6. Patuxent River estuarine sediment loads and budget. Loads are in Mt/yr.

MANAGEMENT APPLICATIONS. The sediment budgets developed in this study allow an increased understanding of the patterns of sediment transport, erosion, and deposition in Chesapeake Bay estuaries. For example, in the lower York River, the large difference in loads between stations LE4.3 and LE4.2 suggests a tendency for erosion between these two stations (Figure 8a). However, there is not enough shoreline erosion (most plausible long-term source of sediment) to account for the difference. The York River in particular is highly energetic, with high levels of resuspended sediment (Dellapenna et al. 1998) that may account for a substantial portion of the calculated load. Thus, bed sediment may be exported from between these two stations during the non-storm conditions captured by monitoring.
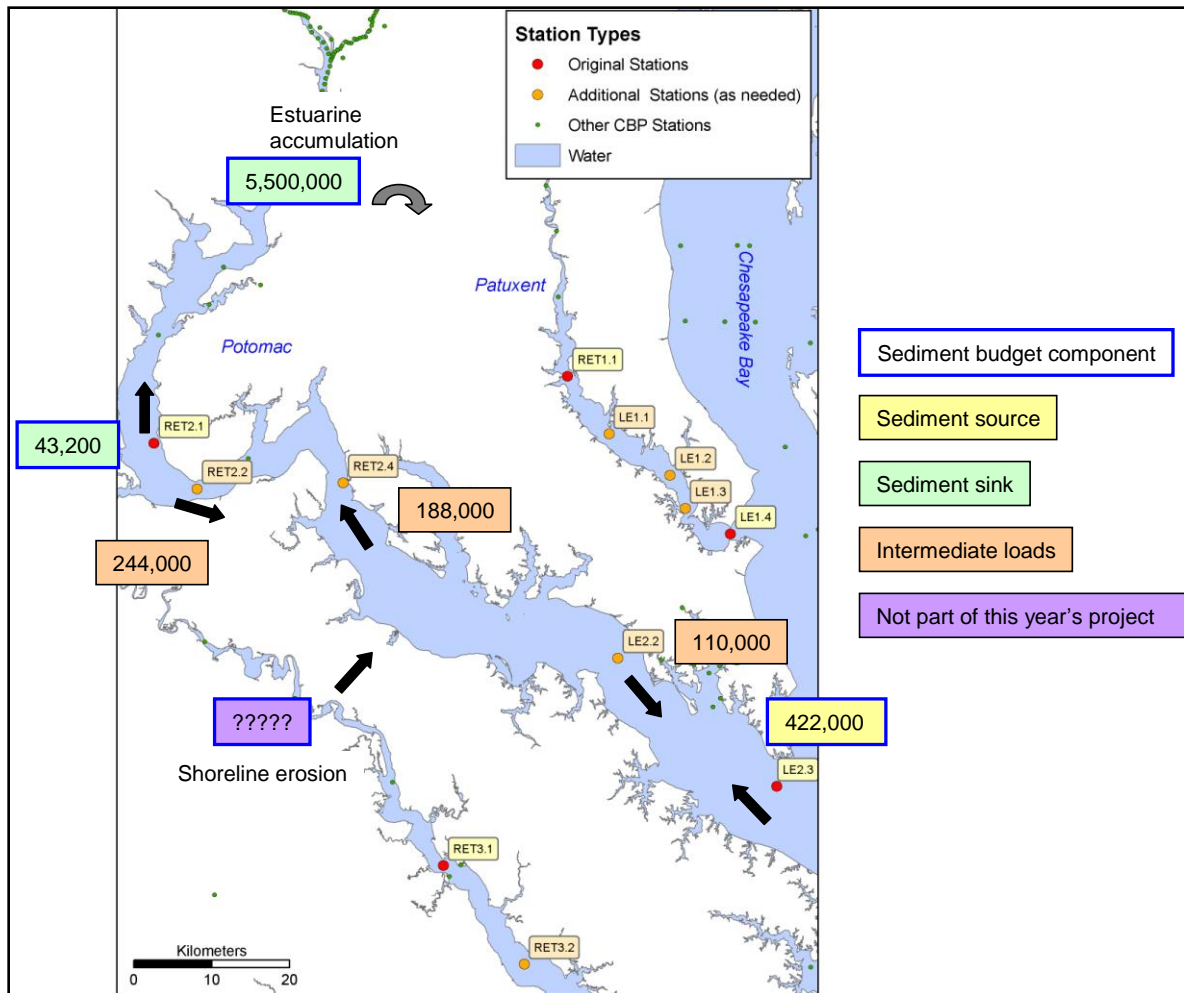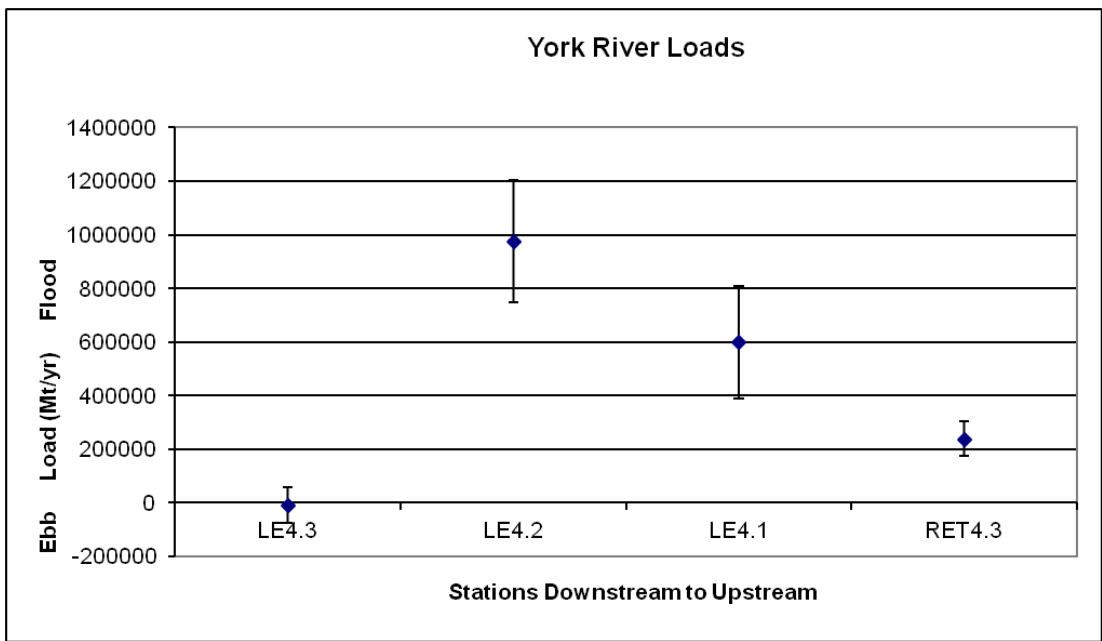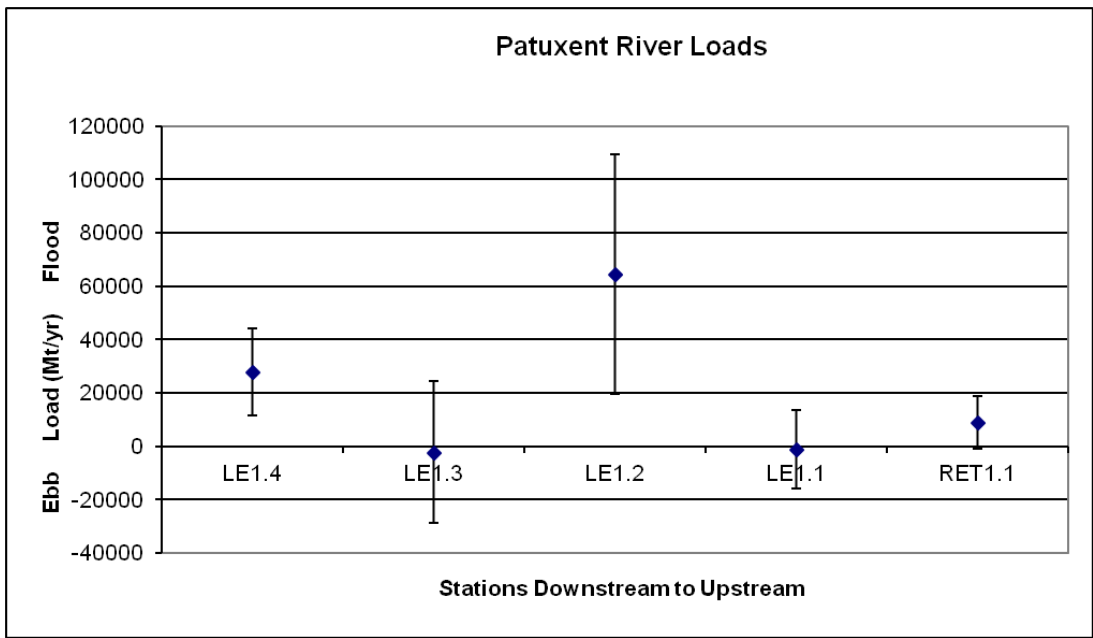
Figure 7. Potomac River estuarine sediment loads and partial budget. Loads are in Mt/yr.

In the Patuxent River, the large load at station LE1.2 may be due in part to sediment input from the adjacent tributary. Sediment from upland erosion in the Coastal Plain usually is input through streams. It is thought that the significance of upland erosion in this type of sediment budget is minimal because of the low relief (Gellis et al. 2007). The relative contribution of the erosion of sediment from the land surface rather than from stream corridors is not well understood in the Chesapeake Bay basin (Gellis et al. 2007). Further investigation of sediment distribution in these systems would contribute information about cumulative input from the numerous small tributaries of an estuary, and help with water quality and shoreline management decisions.

The methods developed and used in this study are transferable to other systems. Sediment loads and sediment budgets from other rivers in the Bay would help clarify the overall picture of sediment transport and distribution, and assist regional sediment management efforts in Chesapeake Bay.
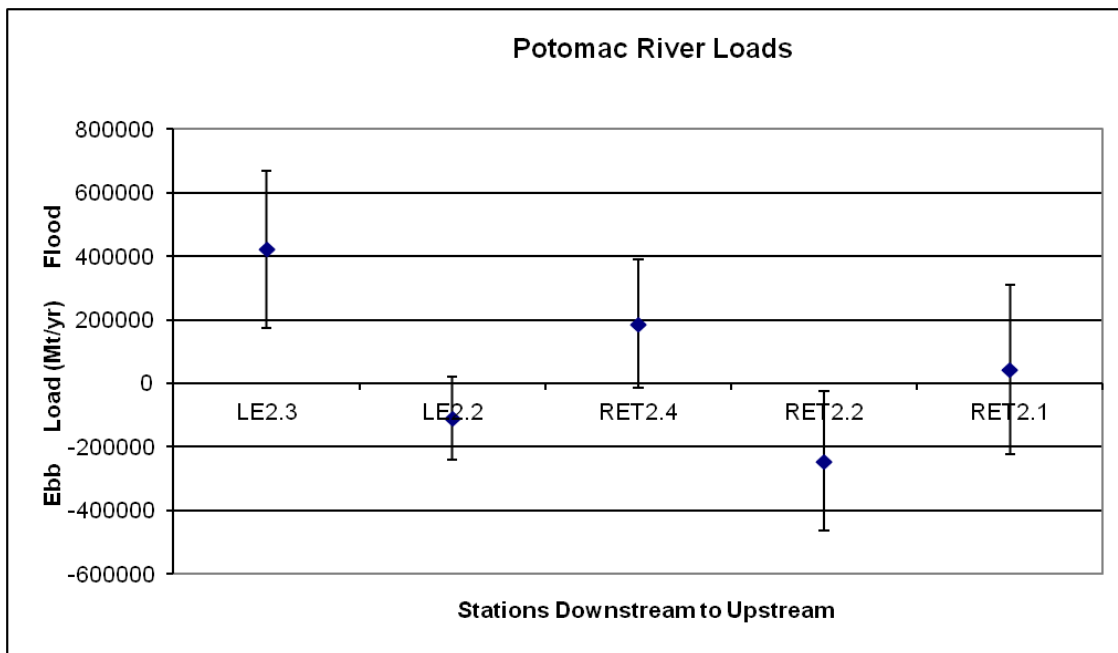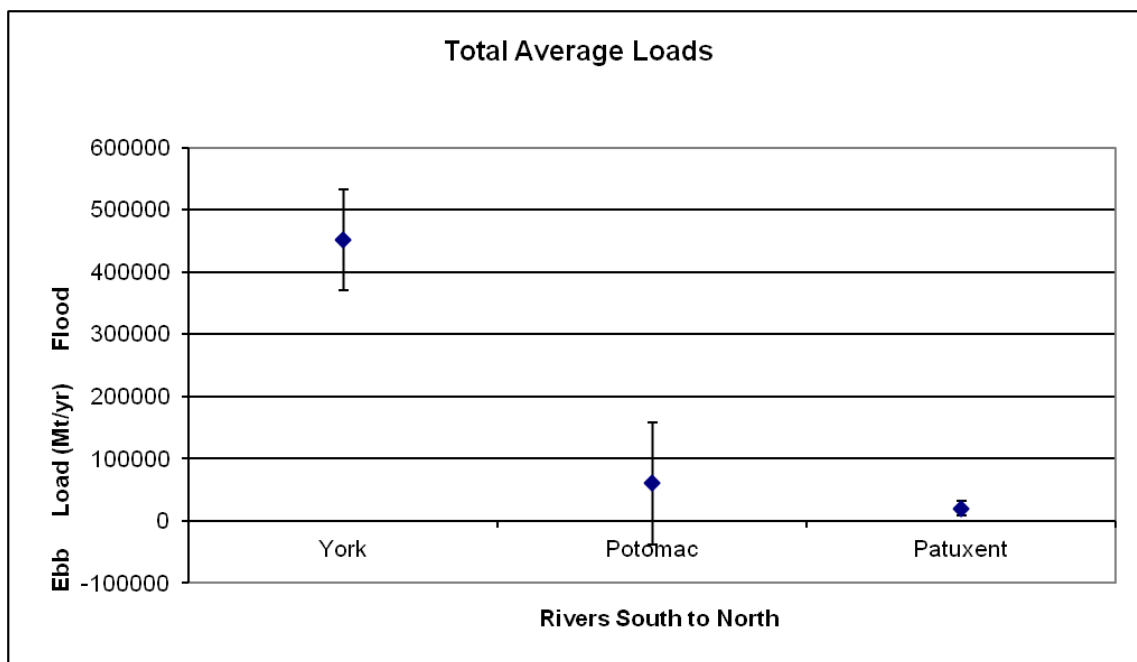
a. York River loads.

b. Patuxent River loads.

Figure 8. Magnitude and direction of estuarine sediment
loads for each station, and of average loads for each river
(flood is positive; ebb is negative). (continued)

c. Potomac River loads.

d. Total average loads.

Figure 8 (continued). Magnitude and direction of estuarine sediment loads for each station, and of average loads for each river (flood is positive; ebb is negative).

ADDITIONAL INFORMATION. This Coastal and Hydraulics Engineering Technical Note (CHETN) was prepared as part of the Regional Sediment Management (RSM) program, and was written by Dr. Julie D. Herman, Center for Coastal Resources Management, Virginia Institute of Marine Science (VIMS), Gloucester Point, VA, for the US Army Engineer District, Baltimore (NAB). Herman and Friedrichs (2010) contains additional information, data, and figures, and is available at http://ccrm.vims.edu/research/water_sediments/suspended_sediments/index.html

Carl Friedrichs, Department of Physical Sciences, VIMS, collaborated on calculating the estuarine sediment loads. This project was supported by NAB as part of the Corps' Regional Sediment Management (RSM) program. This work supports the RSM efforts in the Chesapeake Bay for both the Baltimore District and Norfolk District. The RSM point of contact (POC) for the Baltimore District is Michele Gomez. Additional information pertaining to RSM can be found at the Regional Sediment Management web site http://rsm.usace.army.mil

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> http://chl.erdc.usace.army.mil/library/publications/chetn/pdf/chetn-xiv-23.pdf

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ACRONYMS AND ABBREVIATIONS.

Term	Definition
CBP	Chesapeake Bay Program
CHETN	Coastal and Hydraulics Engineering Technical Note
CHL	Coastal and Hydraulics Laboratory
ERDC	Engineer Research and Development Center
FSS	Fixed Suspended Solids
LE	Lower Estuary
LIDAR	LIght Detection And Ranging
NAB	North Atlantic, Baltimore
NOAA	National Oceanic and Atmospheric Administration
RET	River-Estuary Transition
RSM	Regional Sediment Management
SSC	Suspended Sediment Concentrations
TIN	Triangulated Irregular Networks
TSS	Total Suspended Solids
USACE	US Army Corps of Engineers
USGS	US Geological Survey
VIMS	Virginia Institute of Marine Science